EXPLORING THE SHALLOW SUBSURFACE OF MARS WITH IMAGING RADAR: SCIENTIFIC PROMISE AND TECHNICAL RATIONALE

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OVERVIEW. Remote sensing by Earth-based and orbiting instruments has provided a wealth of information on the geologic and climate history of Mars that bears directly on the question of past and current habitability. Recent experience with radar imaging and sounding of the Moon, terrestrial arid regions and glaciers, and volcanic, sedimentary, and polar layered deposits of Mars shows that a significant part of the geologic record is recorded in features buried by mantling debris, layering due to ice property variations, and in the physical nature of deposits formed by volcanism, sedimentation, or impact. Global information on martian near-surface features and physical properties represents a great untapped aspect of the search for habitable zones and evidence of past climate. Imaging radar measurements at wavelengths of 30-60 cm can penetrate several meters of mantling material and 10's of meters into ice, and a highly capable synthetic aperture radar (SAR) instrument is well within the scope of a Discovery or Scout-class mission.

I. SCIENTIFIC VALUE OF PROBING THE SHALLOW SUBSURFACE

Geologic and hydrologic processes leave their marks on the visible landscape, the layering of deposits beneath the surface, and often in the particle size distribution of materials that blanket the bedrock. Visible and infrared remote sensing offers phenomenal views of landforms and their general composition, but remains limited to the upper surface (Figure 1). The properties of a muted, underlying feature may be discerned, and aspects of subsurface physical properties may be inferred from exposed rocks or scarp faces, but these are often localized observations. Given the ubiquitous aeolian cover and the importance of establishing the record of past climate, volcanism, and other processes on Mars, there is a need to directly characterize, on the global scale, the physical properties of surface mantling deposits and to map process-diagnostic landforms beneath these layers.

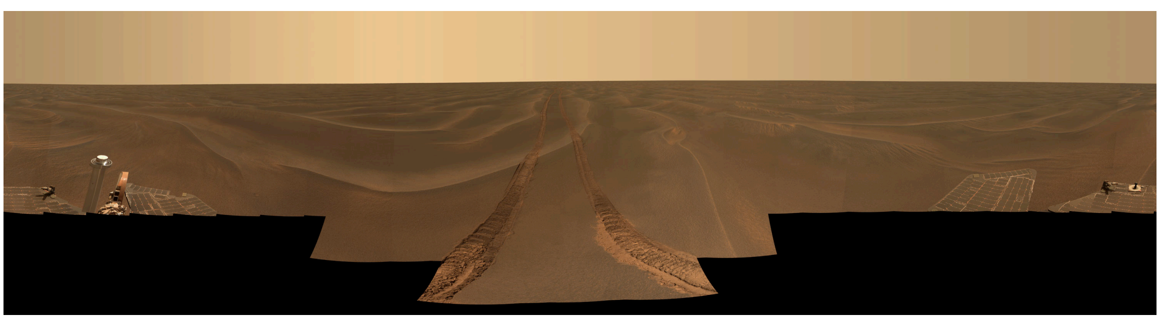

Figure 1. What Lies Beneath? Fine material blankets the martian surface along the Opportunity rover traverse.

Detection and mapping of buried geologic features by radar is confined to arid regions on the Earth due to the presence of water in almost any soil. The most recognized example is the detection by the Shuttle Imaging Radar system of ancient river channels related to trans-African drainage before the formation of the Nile [McCauley et al., 1982]. On Mars, there is no appreciable free water in mantling material so radar penetration to reveal buried geologic features will be commonplace, as confirmed by Arecibo observations [Harmon et al., 1999]. The entire range of process-diagnostic landforms awaits discovery: fluvial channels, ancient shorelines, lava flows, aeolian

structures, impact craters and debris fields, and ice-related features such as patterned ground, pingoes, and moraines. The great advantage of imaging radar is the capability to map such features over vast areas, greatly extending and enhancing the science value of targeted optical observations where a landform is exposed at the surface.

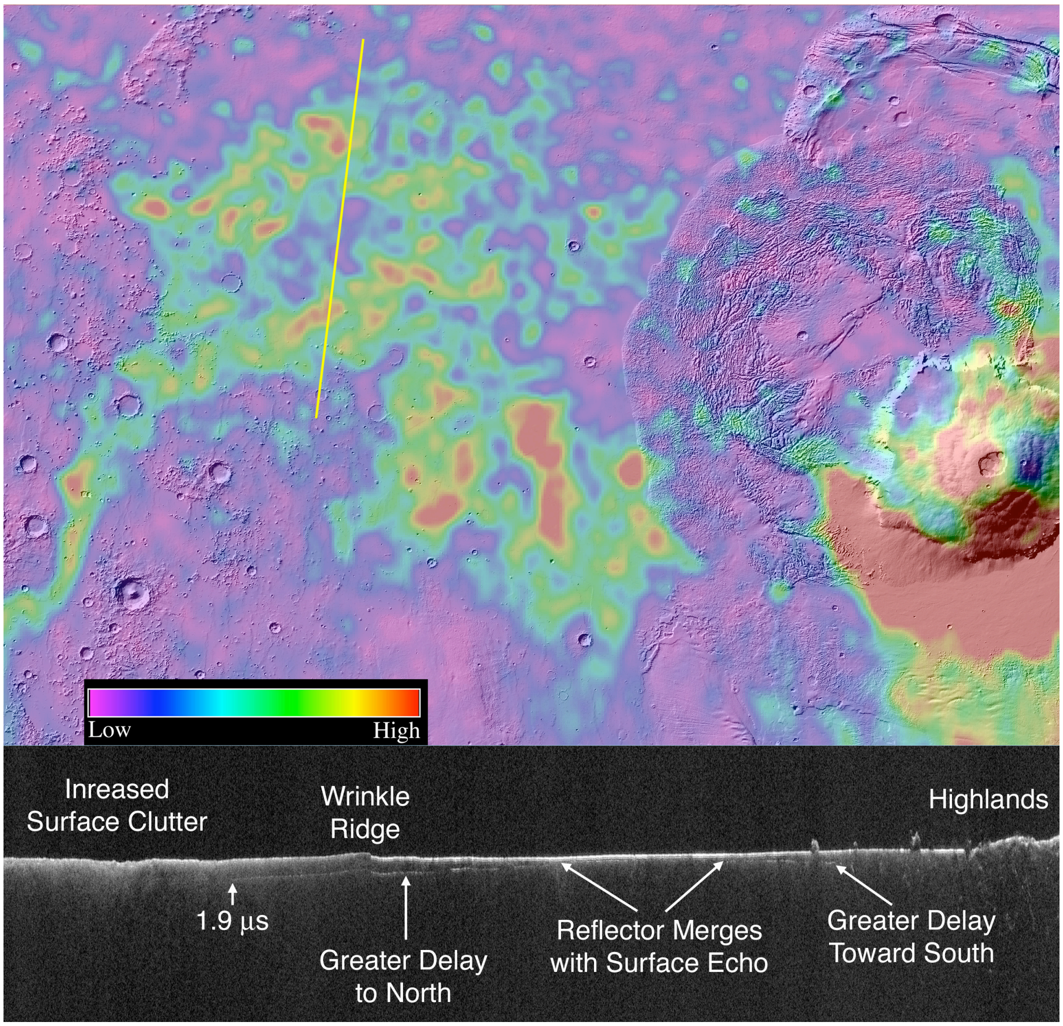

Figure 2. Observational Synergies. Top - Arecibo 12.6-cm radar backscatter data for Amazonis Planitia and Olympus Mons on shaded relief map, color-coded to show echo strength. High backscatter is associated with rugged lava flows from the Cerberus Fossae vents at lower left, and from Tharsis volcanoes to the east. Bottom - SHARAD radargram from the north (left) to south (right) across Amazonis Planitia (approximate track location shown by yellow line in radar image), showing a reflector associated with base of Vastitas Borealis sediments at maximum depths of 100-170 m.

This approach is well demonstrated in the synergy among visible, near infrared, thermal IR, imaging radar, and sounding radar data in understanding Amazonis Planitia (Figure 2). In this roughly circular region west of Olympus Mons, a long history of volcanic and sedimentary infilling have left deposits that can only be unraveled with the full range of remote sensing techniques. MOLA topography data reveal a nearly flat surface at 10's of meter scale, due to fine aeolian material as shown by thermal IR

mapping and HiRISE images. Beneath this mantle in many places are rugged lava flows, representing the last great episodes of flooding from vents in the Cerberus Fossae region. These flows are detected by their high radar backscatter at 12.6-cm wavelength, which can penetrate the few meters of overlying dust. Finally, SHARAD data reveal a single discrete dielectric interface at 30-170 m depth that slopes from the highland boundary downwards toward the northern plains, and represents the base of the Vastitas Borealis sediments atop ancient Hesperian lavas [Campbell et al., 2008]. An imaging radar with much higher resolution and sensitivity than the Arecibo data could greatly improve our understanding of the interplay between processes in this region, and particularly focus on volcano-ground ice interactions suggested by localized explosive landforms.

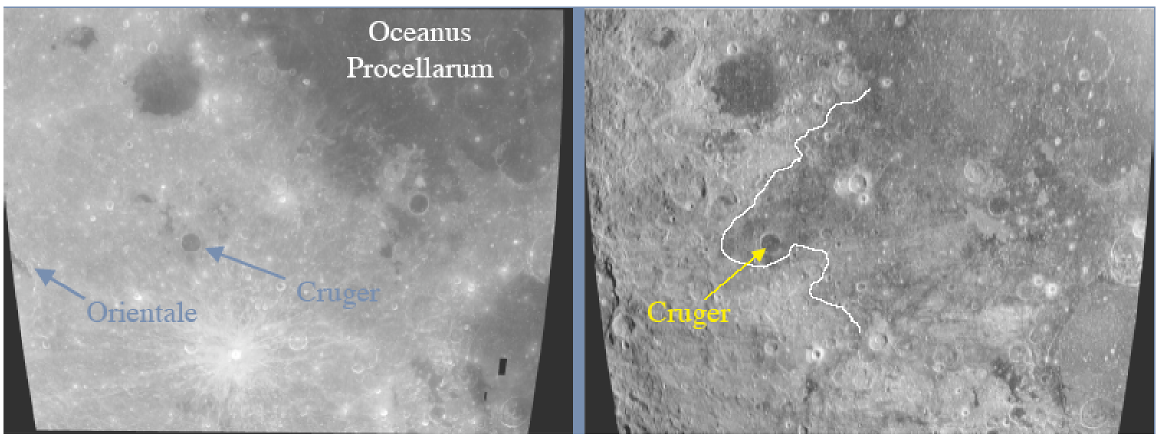

Figure 3. Probing Thick Deposits. Clementine 750-nm (left) and 70-cm radar (right) images of the region between SW Oceanus Procellarum and the Orientale Basin. Note that the region surrounding the mare-filled crater Cruger has similar optical properties to other highland-rich terrain, but the radar penetrates 30-40 m to detect basalt, mixed into the regolith, from an ancient lava complex (white outline) connected with Procellarum.

It is not necessary that imaging radar always reflect from "bedrock". Recent experience with lunar radar mapping at 12.6-cm and 70-cm wavelengths shows that important information about surface formation and evolution processes is contained in the rock population and microwave loss properties of mantling deposits. Examples of this type of probing include studies of mega-regolith thickness based only on the degree of blockiness in crater ejecta blankets [Thompson et al., 2009], which could be of interest in examining the depth of basin ejecta that remains in the martian highlands. Long-wavelength radar images of the Moon also reveal abrupt changes in the composition of thick regolith layers with depth, as in a case where highlands material from the Orientale impact blankets ancient mare basalts (Figure 3). This same type of analysis could be used to probe the martian ground ice layer discovered by Odyssey GRS, to search for shallow ice lenses in an otherwise homogeneous background matrix, or to characterize physical variations in the Medusae Fossae Formation. While most of the examples from lunar work are confined to impact and volcanic processes, the concepts are readily extended to thick deposits produced by wind, water, and ice-related processes.

The martian polar layered deposits present an opportunity for two uses of an imaging radar system. Because the microwave losses in ice are very small, even a 30-60 cm signal could penetrate 10's of meters into the upper portion of the caps. Similar depths of

probing have been achieved in low-loss lunar highlands material [Campbell and Hawke, 2005]. Imaging radar reveals regional variations in the icy surface layers of the Galilean satellites, even at coarse resolution [Ostro et al., 1992], and the detailed images of spatial variations in echoes across the martian caps will likely reveal differences in local dust abundance due to varying deposition rates and later ablation/sublimation. Perhaps even more directly useful will be a nadir-view probing of the caps by the SAR system. With properly chosen bandwidth, a SAR could act as a vertically resolved sounder for the upper few tens of meters in ice. This would fill in the crucial spatial gap left by the SHARAD system, and complete our understanding of the packet structure potentially related to orbital variations [Putzig et al., 2009].

II. Technical Approach and Rationale

The subsurface of Mars has been observed thus far by three sensors: the MARSIS [Picardi et al., 2005] and SHARAD [Seu et al., 2007] radar sounders and the Arecibo imaging radar system [Harmon et al., 1999]. Sounders differ from imaging radar in transmitting the radio signal toward the nadir and measuring echoes as a function of time delay. Some improvement in the along-track resolution is achieved by Doppler processing, but these are fundamentally a footprint style of measurement which build up a vertically-resolved cross section (or radargram) of the subsurface as they travel above the ground. Imaging radar (SAR) looks off to the side, and uses both the delay and frequency information in the echoes to form a map of high-resolution pixels. There is no discrimination within a given pixel as to the depth of a particular component of the echo, but the resulting image typically reveals either a discrete geologic interface (buried lava flows, crater deposits, rough channel beds, etc.) or the volume abundance of wavelength-scale rocks within the probing depth for thicker "regolith" layers. The sounding and imaging measurements are highly complementary, and can be used to build up a complete picture of geologic/hydrologic conditions from the surface to hundreds of meters below the ground. We examine below some basic topics in defining the optimum SAR sensor characteristics.

Which Wavelength is Best? The choice of operating wavelength for a cost-effective, single-frequency system is a trade: longer wavelengths deliver greater penetration depth, but for a fixed antenna size the system gain declines with wavelength. At the same time, most natural surfaces become "smoother" at larger horizontal scales, so a side-looking radar will eventually see nothing if the wavelength becomes too large. A simple analysis of these effects [Campbell et al., 2004] suggests that wavelengths of 30-60 cm define the optimum match between penetration depth and roughness changes in detecting buried geologic features.

How Deep Will We See? Radar penetration into geologic deposits is limited by attenuation in the constituent materials. Cold ice has extremely low losses, feldspar-dominated rocks like lunar anorthosites have quite low attenuation, and basalts exhibit a wide range depending upon the abundance of lossy minerals such as ilmenite [Carrier et al., 1991]. For Earth applications, moisture within the target materials is often the limiting factor in radar losses, but for Mars this behavior has not been observed by either

of the sounding radar systems. Evidence to date shows that loss tangents at microwave frequency for volcanic deposits like the Medusae Fossae Formation [Watters et al., 2007] and sedimentary material like the Vastitas Borealis Formation [Campbell et al., 2008] are typically 0.01 or less, easily permitting a 30-60 cm radar signal to penetrate 5 m or more. Losses in the polar layered terrains [Phillips et al., 2008] and perhaps some lobate debris aprons [Holt et al., 2009; Plaut et al., 2009] are very much lower, and this same SAR signal could reflect from interfaces at depths up to a few 10's of meters. The detection of rough lava flows in many areas of Mars by the Arecibo 12.6-cm wavelength imaging system, even in areas clearly mantled by a few meters of fine material [Harmon et al., 1999], supports the notion that microwave losses are relatively modest in these dry materials.

What is the Image Resolution? There is a fundamental trade between penetration depth and horizontal spatial resolution in the use of radar systems to probe the subsurface. A synthetic aperture radar can deliver very fine (meter-scale) horizontal spatial resolution for surface images, with a sensitivity set by the maximum transmitted power and the size of the antenna. This sensitivity, typically described by the noise-equivalent backscatter coefficient, must be adequate to distinguish smooth, "radar dark" areas from rough, "radar bright" terrain against the noise background. Assuming power and antenna size to be limited by spacecraft resources, probing beneath the surface requires greater sensitivity obtained at the cost of more coarse horizontal resolution. An imaging radar system with desired penetration depth of 5-8 m in basalt-derived dust can achieve horizontal spatial resolution of 15-18 m, comparable to THEMIS visible-wavelength maps.

***What is Required*?** The science objectives discussed above can be met by a single-frequency, dual- or quad-polarization SAR instrument that uses a 6-m deployable mesh antenna. Taken together, these components require about 100 kg of payload mass, and use about 60 W of orbit-average power to complete a global map within 12-18 months. The instrument design poses no technical challenges, since space-borne SAR is a mature technology, and deployable antennas up to 18 m in diameter are now regularly used for Earth communications satellites. Ground processing of radar data has likewise advanced dramatically since the Magellan era, and even a multi-polarization dataset for the entire surface of Mars can be managed with modest computing resources (the Earth-based lunar radar mapping effort at 70-cm and 12.6-cm wavelength has been accomplished with a few desktop machines). For optimum coverage and signal-to-noise quality, a circular orbit at 300-400 km altitude is required.

III. CONCLUSIONS

Large regions of Mars are masked by mantling debris that can be "peeled away" by imaging radar. Beneath these deposits lies a more complete picture of the martian geologic record, and hence the preserved signatures of past climate and habitability. Even where the bedrock is far below a developed regolith, a long-wavelength probing system can reveal dramatic differences in physical properties often unsuspected from visible or infrared images. In the polar deposits, a SAR system used in a sounding mode can fill in

the vital gap in our knowledge of the upper few tens of meters, where the record of the most recent deposition and losses is preserved. An instrument capable of these investigations on the global scale is well within the scope of a Discovery or Scout-class mission.

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